EOS ® orthopaedic imaging system to study patellofemoral kinematics : Assessment of uncertainty

Charaf Azmi, Sandra Guerard, Xavier Bonnet, François Gabrielli, Wafa Skalli

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C. Azmy[a,*], S. Guérard[b], X. Bonnet[b], F. Gabrielli[b], W. Skalli[b]

[a] *Villeneuve Saint-Georges Interborough hospital center, 40, allée de la Source, 94195 Villeneuve Saint-Georges cedex, France*
[b] *CNRS, Arts et Métiers Biomechanics Laboratory, Paristech, École nationale supérieure d'Arts et Métiers, 151, boulevard de l'Hôpital, 75013 Paris, France*

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Summary
Background: Accurate knowledge of knee joint kinematics, especially patellofemoral joint kinematics, is essential for prosthetic evaluation so as to further improve total knee arthroplasty performances. Improving the evaluation of the functioning of the extensor apparatus appears, in this respect, particularly important in this optimization effort.
Objectives: The aim of this study was to propose a new experimental setup for the analysis of knee joint kinematics and to validate its relevance in terms of accuracy and uncertainty. The technique developed herein combines 3D reconstruction imaging with the use of a motion capture system.
Material and methods: Eight pairs of fresh-frozen cadaver specimens with no evidence of previous knee surgery were studied using a new test rig where the femur remains fixed and the tibia is free to rotate. The flexion—extension cycles were executed using computer-controlled traction of the quadriceps tendon combined with an antagonist force applied to the distal part of the tibia. Knee joint kinematics were tracked using an optoelectronic motion capture system after a preliminary stage of data acquisition of bone geometry and markers position. This stage was carried out using a new digital stereophotogrammetric system, EOS®, combined with specific 3D reconstruction software that also determined the coordinate system used in the kinematic analysis. The resulting uncertainty was assessed as was its impact on the estimated kinematics.
Results: Test results on eight knees validated the setup designed for the analysis of knee joint kinematics during the flexion—extension cycle. More specifically, the statistical results show that measurement uncertainty for rotations and translations remains below 0.4 and 1.8 mm, respectively, for the tibia and 0.4 and 1.2 mm for the patella (±2 S.D. for all four measurements).

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* Corresponding author.
E-mail address: charafazmy@hotmail.com (C. Azmy).

Discussion: The combination of 3D imaging and motion capture enables the proposed method to track the real-time motion of any bone segment during knee flexion—extension cycle. In particular, the new test rig introduced in this paper allows in vitro measurements of the patellofemoral and tibiofemoral kinematics with a good level of accuracy. Moreover, this personalized experimental analysis can provide a more objective approach to the evaluation of knee implants as well as the validation of the finite-elements-based models of the patellofemoral joint.

Introduction

A 3D analysis of the knee joint, whether a native joint [1,2], an implanted knee [3,4] or a knee presenting ligament laxity [5,6], is required for a more objective and quantitative assessment of the relations between the pathological lesions, the physical signs, and possibly the functional signs. Today, kinematic assessment has been widely studied in the literature [7,8] during in vivo and in vitro experiments [9—11]. Several techniques have been used during in vitro studies: stereophotogrammetry [12,13], passive markers [14,15], active markers [16], goniometry, and motion capture systems. However, the quantitative assessment of prosthetic implants continues to be challenged by patellofemoral joint kinematics, whether or not there is patella resurfacing. Although failures related to patellofemoral joint complications in total knee arthroplasties (TKAs) have been reduced, this result was obtained only by modifications directly on the patellofemoral joint (e.g., postioning in rotation that is better adapted to the femoral component). This quantitative 3D assessment therefore still needs further development to improve the design of the implant components, thus optimizing the functioning of the extensor apparatus.

The objective of this study was to propose a new method that could provide information on the kinematics of a given knee by combining 3D reconstruction [17] and optoelectronic movement tracking of the knee in flexion—extension. This method was used to describe the in vitro kinematics of eight lower limbs in controlled load conditions. All measurement uncertainties were quantified so as to calculate the method's overall uncertainty and to validate the relevance of the test rig in terms of accuracy and uncertainty. Uncertainty is a notion that takes into account random errors as well as systematic, uncontrolled errors.

Material and methods

The cadaver specimens

Five left lower limbs and three right lower limbs, harvested from subjects aged 58 to 72 years and fresh-frozen, were studied. The eight knees were healthy with no advanced knee joint osteoarthritis or ligament laxity and presented no recurvatum. The main characteristics of the cadaver specimens are reported in Table 1. The specimens were frozen at $-20\,^{\circ}$C, then thawed at room temperature 24 h before the trial. The specimens were tested at room temperature with water vaporization during the tests.

Specimen preparation protocol

The cadaver specimens were prepared by excising the soft tissue except for the quadriceps tendon, the knee's capsuloligamentous complex, and the superior and inferior tibiofibular ligaments.

Experimental setup

The device used, developed and validated by the Paris ENSAM's Laboratoire de BioMécanique LBM, CNRS UMR 8005 in successive experiments, has resulted in a knee experimental setup that has evolved from a test rig where the tibia is fixed [18] to a setup with a fixed femur.

Tripods with passive infrared markers were attached to the femoral diaphysis, the anterior side of the patella, and the proximal metaphyseal—diaphyseal junction of the tibia. Finally, the femur was fixed on the trial setup, providing a test rig comprising an assembly with a fixed femur allowing continuous mobilization of the cadaver knee through a servo-actuator that places the quadriceps tendon under traction. A 50-N return strength was applied to the tibial pilon toward the center of the femoral head (Fig. 1), leaving the tibia free to rotate.

Measurements of marker movement within 6 degrees of freedom (three rotations and three translations) were obtained using an optoelectronic detection system that can deduce the kinematics of the bone specimens tested. These movements were calculated during data processing and provided displacement curves in relation to the flexion—extension angle of the knee being tested. Each specimen had been subjected to six flexion—extension cycles beforehand and showed no hysteresis phenomena.

Data acquisition and processing

Data on the positions in space of the different specimens during flexion—extension motion were continuously acquired with the POLARIS® optoelectronic motion capture system (NDI, Waterloo, Ontario, Canada) (acquisition frequency, 60 Hz). This required nine passive markers distributed on three tripods rigidly attached to the femur, tibia, and patella (Fig. 2).

To express the displacements measured in an anatomic coordinate system in relation to the femur, the knee was placed in the EOS® system such that precalibrated digital radiographs could be obtained along two simultaneous orthogonal incidences: AP and lateral. A reconstruction algorithm described by Laporte et al. [17] provided the 3D

Table 1 Characteristics of the anatomic specimens tested.

Reference	PA04028	PA04029	PA04030	PA04034	PA04035	PA04036	PA04038	PA04039
Age	65 years	65 years	58 years	60 years	60 years	71 years	72 years	72 years
Sex	M	M	M	F	F	M	F	F
Direction	L	R	L	L	R	L	L	R

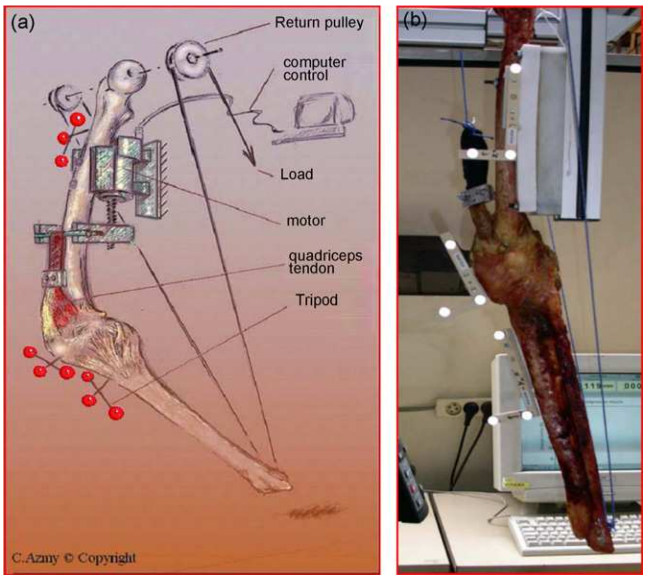

Figure 1 Diagram (Courstesy C. Azmy) and experimental set up on photograph.

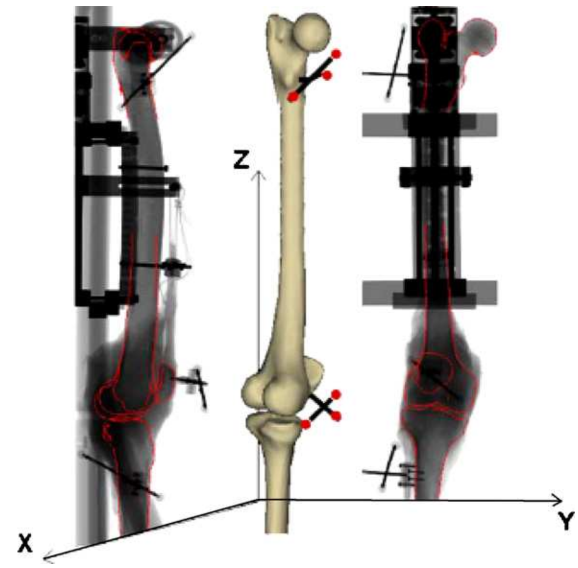

Figure 3 Knee joint 3D reconstruction from two stereophotogrammetric pictures (Laporte et al. [17]): The tripods' 3D position, determined using the EOS® device, transfers the anatomic coordinate system. The EOS® is an x-ray imaging system resulting from the collaboration between Prof. J. Dubousset, Georges Charpak (Nobel prize in physics), Biospace, the ENSAM Biomechanics Laboratory (CNRS UMR 8005, ParisTech) and the Imaging and Orthopaedics Laboratory (LIO) located in Montreal.

reconstruction of the three bone specimens (Fig. 3) as well as the tripods. Then, the relation between the markers (measured by the optoelectronic system) and the bone specimens was determined by matricial calculation.

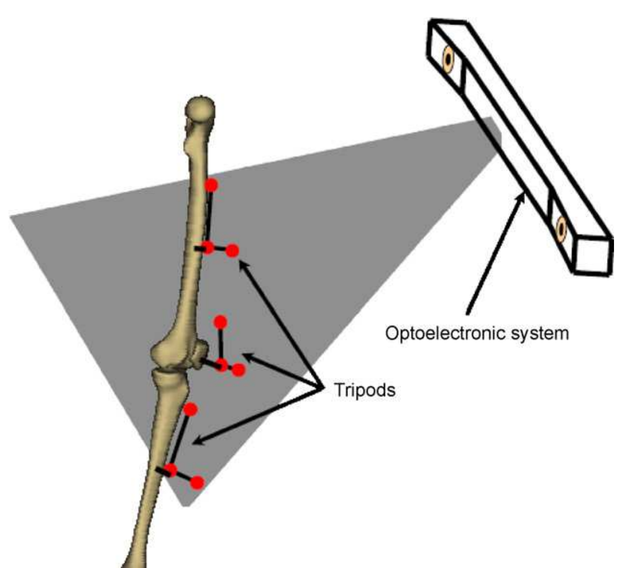

Figure 2 Optoelectronic device used to measure the three bone motions and lower limb marker position.

Reconstruction algorithm

The EOS® system directly captures digital images. The resulting data is processed using software developed in collaboration with the Paris ENSAM's Biomechanics Laboratory and the ETS Imaging and Orthopaedics Laboratory (LIO) located in Montreal. This software is based on the non-stereo-corresponding contour (NSCC) algorithm, which identifies coordinate systems as well as contours. It uses a preexisting generic 3D object atlas. These objects are broken down into definitively defined anatomic regions that will be used to carry out different reconstructions.

The 3D reconstruction took place in the following steps:

- identification on radiographs of anatomical points and 2D contours to be compared to the generic objects;
- iterative adjustment after the two data are associated in the radiographic planes;
- kriging, which provides a personalized 3D model through iterative deformation [19].

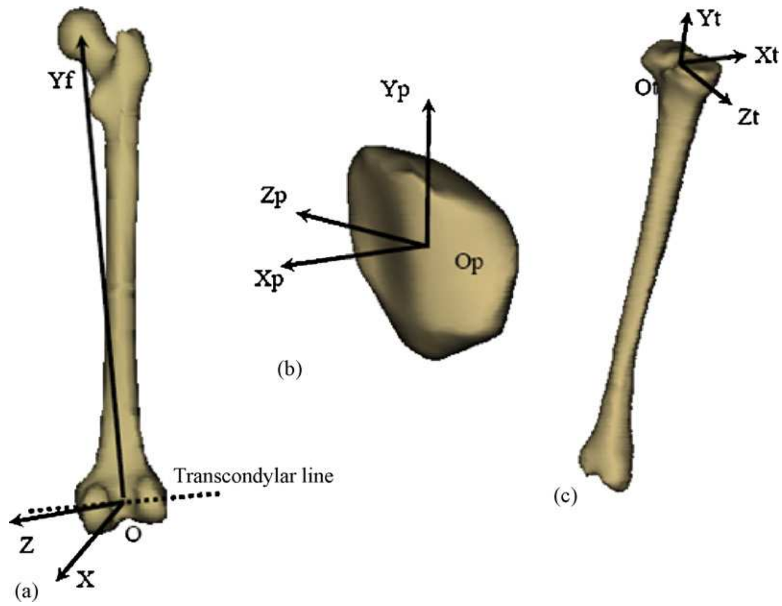

Figure 4 Determination of femoral (a), patellar (b) and tibial (c) coordinate system.

Definition of anatomic coordinate systems

The anatomic coordinate systems used (Fig. 4) were defined as follows.

For the femur

The origin of the femoral coordinate system, Of, was located in the middle of the [m, l] interval, with m and l the centers, respectively, of the two condylar spheres (medial and lateral) constructed by approximation to the least squares of the posterior part of the two condyles.

The *Y*f-axis went through Of and the center of the femur head (spherical in shape), the *X*f-axis was the line perpendicular to Of at the plane formed by the *Y*f-axes and the segment [m,l]. The *Z*f-axis was the line perpendicular to Of at the plane formed by the *X*f-axes and the *Y*f-axis. The *Z*f-axis was directed medially for a right knee and laterally for a left knee (Fig. 4).

For the patella

The patella was regionalized: the lateral edge, medial edge, and tip. For each region considered, the corresponding barycenter was calculated: ''m'' for the medial edge, ''l'' for the lateral edge, and ''p'' for the tip. The beginning of the Op coordinate was located in the middle of segment [l, m], the *Y*p-axis started at point p and continued toward the center Op, the *Z*p-axis belonged to the plane formed by the three points (l, m, and p) and was orthogonal to *Y*p at Op. *Z*p was directed medially for the right knee and laterally for the left knee and the *X*p-axis was orthogonal to Op on the plane formed by *Y*p and *Z*p [20].

For the tibia

The origin of the tibial coordinate Ot was the intersection of the mechanical axis of the tibia and the surface of the tibial plateau, the *Y*t-axis was the mechanical axis of the tibia (going through the middle of the talar dome and the middle of the peaks of the tibial intercondyloid eminence), the *Z*t-axis was the projection of the tibial superior articular surface segment along a plane perpendicular to *Y*t and the *X*t-axis was the vectorial product of *Y*t and *Z*t.

Kinematics

This was a continuous kinematic analysis calculated taking each position into account in relation to the femur (the fixed segment). Patellar motion was indexed to the knee's range of motion. The sector studied progressed from 0° to 120°, with the reference position chosen the position in which the knee was locked in extension; none of the knees presented recurvatum.

A matricial calculation gave the kinematics of the marker tripods and consequently (with the transformation matrices) the kinematics of the bone specimens to which they were attached. The kinematics were studied for 6 degrees of freedom: three rotations and three translations. These components were defined as follows:

- three rotations (Fig. 4):
  - o abduction—adduction (rotation around the *X*p-axis),
  - o tilting (rotation around the *Y*p-axis),
  - o flexion—extension (rotation of the patella around the *Z*p-axis);
- three translations (Fig. 4):
  - o anteroposterior translation along the *X*p-axis,
  - o proximal — distal translation along the *Y*p-axis,
  - o mediolateral translation along the *Z*p-axis.

Evaluation of measurement uncertainties

Uncertainty is a notion that takes into account random errors and uncontrolled systematic errors; the latter was of particular interest in this study.

Table 2 Evaluation of measurement uncertainties (2 S.D.).

	Rotations around axis (°)			Translations along axis (mm)		
	x	y	z	x	y	z
Uncertainties related to calculation of coordinate system	0.4	0.2	0.6	0.6	0.4	0.6
Uncertainties related to tripod adjustment	0.4	0.8	0.2	0.4	0.4	0.4
Uncertainties related to optoelectronic measurement	0.8	0.4	0.2	0.14	0.14	0.14

The reproducibility of the test setup was certified by *Le Comité français d'accréditation* (COFRAC) accreditation based on the ISO 17025 norm.

Uncertainties related to anatomic coordinate calculations

The uncertainties related to calculating the knee's anatomic coordinates were estimated by measuring reproducibility during 3D reconstruction based on the EOS® radiographs. Nine knees were reconstructed three times by two different operators, making it possible to calculate the deviations associated with bone reconstructions and therefore associated with the anatomic coordinates determined based on these reconstructions. This confirmed the robustness of the coordinate system used.

Uncertainties related to tripod adjustment

The uncertainties related to tripod adjustment corresponded to the interoperator reproducibility errors of the method used to adjust the tripod arm bearings on the EOS® x-rays.

Uncertainties related to optoelectronic measurement

The uncertainties related to the optoelectronic measurement corresponded to the deviations between the true tripod position and the position measured using the passive-marker motion capture system.

Estimation method

Uncertainties were evaluated with Monte-Carlo simulation [21], a method frequently used to estimate uncertainty, with numerical simulation consisting in adding noise to an entry data set to study the effect of this noise on the exit variables. This method can be used even for small samples that are not necessarily normally distributed but whose results can be presented within a normal distribution and therefore in terms of mean and standard deviation. It is also particularly well adapted to evaluating the robustness of the coordinate systems.

Results

Evaluation of measurement uncertainties

Calculated uncertainties related to the study's different data

Table 2 presents the calculated uncertainties related to the study's different data (coordinate calculation, tripod adjustment, and optoelectronic measurement) for different degrees of freedom. All these results are presented for 2 S.D. (corresponding to the 95% confidence interval [CI]).

Uncertainties related to calculating coordinates

Translations. Uncertainties for translations were 0.6 mm along the *X*-axis, 0.4 mm along the *Y*-axis, and 0.6 mm along the *Z*-axis.

Rotations. Uncertainties for rotations were 0.4° around the *X*-axis, 0.2° around the *Y*-axis, and 0.6° around the *Z*-axis.

Uncertainties related to adjusting the tripods

Translations. Uncertainties for translations were 0.4 mm along the *X*-axis, 0.4 mm along the *Y*-axis, and 0.4 mm along the *Z*-axis.

Rotations. Uncertainties for rotations were 0.4° around the *X*-axis, 0.8° around the *Y*-axis, and 0.2° around the *Z*-axis.

Uncertainties related to optoelectronic measurement

Translations. Uncertainties for translations were 0.14 mm along the *X*-axis, 0.14 mm along the *Y*-axis, and 0.14 mm along the *Z*-axis.

Rotations. Uncertainties for rotations were 0.8° around the *X*-axis, 0.4° around the *Y*-axis, and 0.2° around the *Z*-axis.

The uncertainties were for the most part less than 1° for rotations and on the order of 0.5 mm for translations.

Overall uncertainties related to bone segment movement

The overall uncertainties related to patellar and tibia movement expressed in the femoral coordinate system were estimated and are presented, for 2 S.D. (corresponding to the 95% CI), in Table 3.

Uncertainties related to patellar movement

Table 3 Evaluation of motion measurement uncertainties (2 S.D.).

	Rotations around axis (°)			Translations along axis (mm)		
	x	y	z	x	y	z
Overall uncertainties related to tibia movements expressed in femoral coordinate system	0.4	0.4	0.4	1.8	1.5	1.5
Overall uncertainties related to patellar movements expressed in femoral coordinate system	0.4	0.4	0.4	1.2	1.2	1.2

Translations. Uncertainties for translations were 1.2 mm along the *X*-axis, 1.2 mm along the *Y*-axis, and 1.2 mm along the *Z*-axis.
Rotations. Uncertainties for rotations were 0.4° around the *X*-axis, 0.4° around the *Y*-axis, and 0.4° around the *Z*-axis.

Uncertainties related to tibia movement

Translations. Uncertainties for translations were 1.8 mm along the *X*-axis, 1.5 mm along the *Y*-axis, and 1.5 mm along the *Z*-axis.
Rotations. Rotations were 0.4° around the *X*-axis, 0.4° around the *Y*-axis, and 0.4° around the *Z*-axis.

The uncertainties were for the most part less than 1° for the rotations and between 1.5 mm and 2 mm for the translations.

Kinematics of the normal knee: experimental corridors

Data presentation

The values of patellar motion on a particular axis are presented on the *Y*-axis and the degree of knee flexion on the *X*-axis, providing curves illustrating the patellar kinematics for the different knees (Fig. 5). The corridor is said to be wide when the curves are relatively scattered and it is said to be narrow in the opposite configuration. In Fig. 5, the experimental results corresponding to patellar motion expressed in the femur coordinate system are presented for the eight healthy knees tested. Each curve is a mean of six cycles on an anatomic specimen.

Patellar motion

When moving from extension to flexion:

- abduction—adduction (rotation around the *X*p-axis) [Fig. 5(a)]: it did not exceed 8° and progressively increased with flexion of the knee (but not always in the same direction);
- tilting (rotation around the *Y*p-axis) [Fig. 5(b)]: the corridor was wider but did not exceed 8°;
- flexion—extension (patellar rotation around the *Z*p-axis) [Fig. 5(c)]: the patella was flexed in a continuous motion related to knee flexion;
- anteroposterior translation along the *X*p-axis [Fig. 5(d)]: the patella was moved in posterior translation accelerating from 30° knee flexion and able to reach 40 mm.

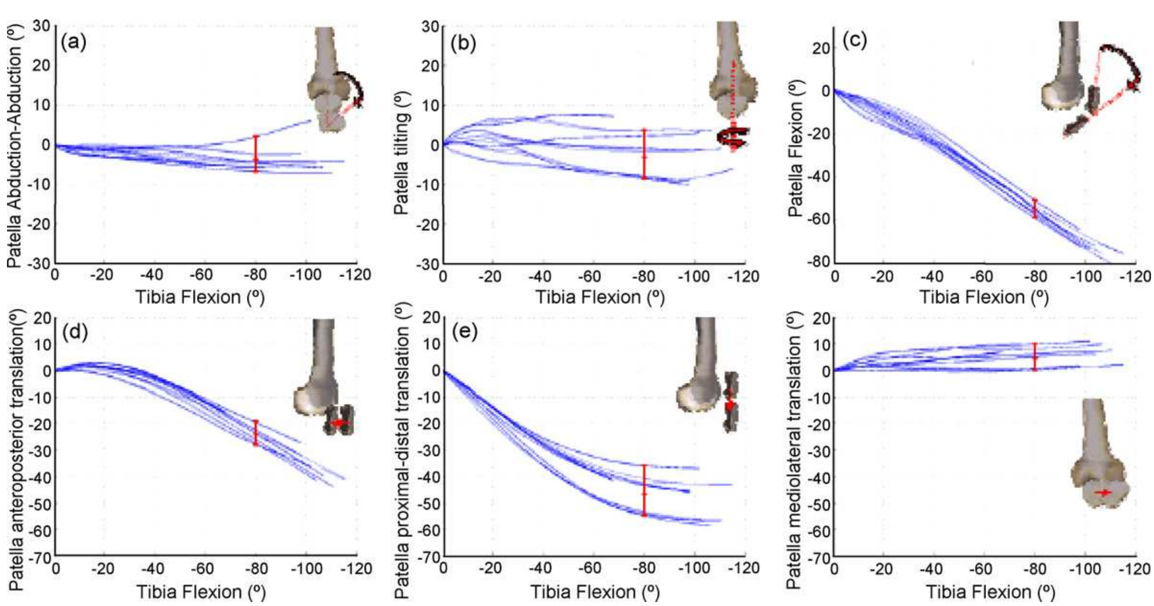

Figure 5 Experimental results: patellar kinematics (rotations and translations) described according to femoral coordinate system within knee flexion—extension cycle.

- proximal—distal translation along the *Yp*-axis [Fig. 5(e)]: this movement regularly followed knee flexion and then slowed beginning at 60° to 80° while showing greater variability.
- mediolateral translation along the *Zp*-axis [Fig. 5(f)]: this did not go beyond 10 mm, increasing from 0 to 20° knee flexion and did not follow the same direction for all knees.

Discussion

The test rig measured in vitro patellofemoral kinematics with a high level of accuracy, making it a reliable tool. Uncertainty was estimated at 1.2 mm for translations and 0.4° for rotations.

Several recent studies have used MRI or stereophotogrammetric analysis (9) to evaluate joint kinematics by interpolating a succession of discrete positions. Other studies combining 3D reconstructions and fluoroscopy provide access to 3D kinematics of the knee during planar movement [22,4]. Other authors suggest combining 3D reconstructions with magnetic systems [23] or with electrogoniometric systems [14] to analyze the kinematics specific to a subject's particular morphology. Three-dimensional reconstructions do indeed increase measurement accuracy because they use coordinate systems adapted to the bone segments studied [24].

Patellar kinematics during a knee flexion—extension cycle can be calculated in two ways: either by considering the successive positions of the patella, referring to the preceding position each time, or by considering each position in relation to a fixed segment. We used the latter method in our trials, with the femur used as the fixed segment [11].

We used the femur as the system of reference rather than the tibia.

Experimental rigs with a fixed tibia [25,26] were intended to reproduce the screw home motion in monopedal weight-bearing. This would have been a determining factor in an in vivo study where asymmetry exists depending on the type of muscle contraction (concentric, excentric) as well as on the use of diverse muscle groups (in relation to the degree of flexion and the relative position of the bone segments). However, we believe that this has little value in vitro since it is difficult to reproduce these parameters experimentally, with the results clearly showing the absence of asymmetry between flexion and extension [10].

The immobile femur was also adopted by many research teams [27,12,2,14,15]. Other than technical simplicity, this choice avoids introducing a measurement bias given that our objective was to study patellar kinematics relative to the femur.

In this example, where the femur serves as the reference system, several options are available. In the literature, authors have described patellar movement relative to the femoral trochlea [10], the posterior femoral condyles [10], the anterior part of the condyles, or in relation to the entire femur. Each method has its advantages and disadvantages. Using the anterior parts of the condyles is not particularly wise because there is great anatomic variation compared to the posterior condyles, which are less prone to this variability and are therefore more reliable. Trochlear groove is interesting because patella centering is an important criterion, but this frame reference cannot always be used, notably in cases of patellofemoral dysplasia [10].

A certain number of test rigs described in the literature [15] only use the distal portion of the femur, which does not provide complete data on the femur geometry and makes the femoral head inaccessible to axis calculation, whereas using the entire femur has the advantage of relating the patellar tracking to the overall morphology of the limb. The technique suggested is based on the acquisition of the 3D morphology of the femur, tibia, and patella using the EOS® system. The envelope thereby reconstructed makes it possible to calculate numerically a system of coordinates related to each bone component to analyze the knee's 3D kinematics.

Axis system [28]

Determining the relative movements of the different bone segments means referring to the segments of the axis systems rigidly linked to these segments, but for each segment, a relevant and robust axis system must be chosen. Choosing the coordinate system is one of the key problems and patellar movement measurements are very sensitive to this [10].

The axis system proposed by Grood and Suntay [in 10] has been widely used in the literature. It was modified by Hefzy and Lafortune [in 10] to analyze the patellofemoral segment. These landmarks are constructed by determining the anatomic points on 2D radiological images [28], which increases the measurement uncertainty.

We have retained the general principle of this coordinate system in that we use a proximal point (the center of the femoral head) and two distal points located at the femoral condyles. The orientation and denomination of the axes were also retained, with modifications essentially in how the anatomic points were determined. This numerical determination of the coordinate system using a calculation taking into account the specific 3D morphology of each specimen allowed us to significantly improve measurement accuracy. This coordinate system's robustness was tested by assessing intraoperator repeatability and interoperator reproductibility.

Knee motion

In studies reported in the literature, the knee was put into motion following different protocols. The in vitro studies used either traction on the quadriceps tendon or weight attached with cables to the different quadriceps muscle groups [10], taking into account the theoretical ratio of the different muscle groups. Both the weight and the direction of the muscle groups were used variably and the influence of these parameters was evaluated in different ways, demonstration of the complexity of the influence of the quadriceps on patellofemoral kinematics [11].

In our study, we applied traction to the quadriceps tendon without differentiating its muscle groups. This was maintained by a clamp connected to a computer-controlled servomotor. Return strength equaling 50 N was applied to the tibial pilon without preventing its rotation during the test.

Even if there is agreement that nearly all of the abnormalities of the patella's tracking are found in the first degrees of flexion, it is important to analyze a broad sector beyond 90° of flexion, or even the entire range, but this depends on the technical capabilities of the method used. Our experimental setup can study nearly all of the flexion—extension sector. This was valuable, notably in the knee arthroplasty tests.

As for the difference in the patellar tracking pattern depending on whether the knee was moved in the flexion—extension direction or in the extension—flexion direction, it generally remained minimal, with the curves most often superimposed (Fig. 5).

In addition, during the knee's flexion—extension, there is automatic rotation of the tibia, which authors have agreed has a real influence on the patellar tracking [16], even if this influence has not been accurately described [10]. This assessment problem may be related to the probable existence of several instantaneous rotation axes during the flexion—extension cycle [29]. The studies that controlled for this rotation [27] show great variability in this aspect of patellofemoral kinematics, which is why a certain number of authors leave the rotation free. We opted for this second solution in our study with a method that allowed us to apply return strength to the tibia at the same time.

Furthermore, a slight varus/valgus laxity exists with no ligament lesion [10], which varies during flexion—extension. Some authors ignore this parameter or leave it free, as in our study, considering that it is an integral part the flexion—extension motion. However, it must be remembered that we found low uncertainty levels on stable knees. In cases of laxity, as may occur on a poorly balanced knee with a prosthesis, we cannot exclude that the level of uncertainty may increase on displacement measurements.

Accuracy of the technique

At this time, the quantitative analysis of the patellofemoral kinematics is difficult to access [10]. The technique's accuracy is an important parameter, given that abnormalities in the patellar tracking may be minimal but could have more significant consequences on stresses, particularly in cases of TKA in which ligament stability is radically modified and the patella parameters are difficult to measure.

The level of accuracy, which is not always indicated in the different studies published, still needs to be quantified more accurately and is expressed in terms of uncertainties on each degree of freedom.

In Katchburian et al. [10], the documented uncertainties correspond to static studies with the degree of knee flexion fixed. They vary from 0.05 to 1.5 mm for translations and from 0.03 to 2° for rotations (Table 4).

The sources of uncertainty on the result of our trials are numerous. Each of these uncertainties was evaluated independently so as to deduce the overall accuracy (Tables 2 and 3): intraoperator reliability and interoperator reproducibility were evaluated during 3D reconstruction, the calculation of the landmarks and the optoelectronic measurement.

The computing sequence for uncertainties was validated by the French Accreditation Committee (COFRAC) and this setup received ISO 17025 certification.

Table 4 Examples of measurement error estimation in in vitro studies [10] (list not exhaustive).

Authors	Translation error (mm)	Rotation error (°)
Reider et al.	0.5	0.5
Ahmed et al. [24]	0.2	0.1
Van Kampen and Huiskes [12]	0.05	0.1
Heegaard et al. [13]	0.05	0.1
Nagamine et al. [2]	0.2	0.5
Goh et al. [14]	1.5	2.0
Kwak et al.	0.05	Not determined
Sakai et al.	0.4	0.5
Hefzy et al.	0.9	0.3

Interpretation of patellar movement from extension to flexion

The values obtained show narrow corridors for translations, flexion—extension, and abduction—adduction, demonstrating the technique's level of accuracy. Many studies show initial medialization of the patella (range, 15 to 40°) and then sometimes a slight lateral translation. As for tilting, the corridor was wider and the results were more variable, in agreement with the data reported in the literature [10].

It could be said that the general pattern of the patellar tracking is globally in agreement with what is described in the literature. However, it should be remembered that the heterogeneity of the studies in terms of definitions and methodology, notably in the choice of coordinate systems, makes it difficult to seriously attempt to compare the results [10]. It has been clearly established that the differences in coordinate systems influence the results significantly.

The mass of the tripods can produce a certain bias and therefore, it is important to center it in the patella. However, the tripod weighs less than 50 g and seems to be insignificant if balancing with the traction of the quadriceps tendon. The systematic error that may result does not preclude the desired comparisons.

More than the absolute value obtained, the level of accuracy and reproducibility of the system is important in this study. This assembly has allowed reproducible and reliable studies, which is particularly useful in comparative studies of knee arthroplasties, in which patellar motion quality is one of the performance criteria.

In addition, this technique to determine the coordinate system can also be used in vivo [30], thus making the most of the EOS® system's lower irradiation compared to other x-ray imaging systems such as CT.

Conclusion

This protocol, combining 3D imaging and continuous tracking, makes it possible to observe bone specimens in real-time throughout the test. This experimental setup can evaluate the patellofemoral and tibiofemoral kinematics in vitro, notably with a knee prosthesis, whether it be a total knee prosthesis with or without resurfacing or a unicompartmental prosthesis, notably the patellofemoral component.

Above and beyond the accuracy and the reproducibility of the setup, the use of a new technique to determine the coordinate system should be noted. This is determined numerically and is in direct relation with the specific anatomy of each specimen.

This test rig opens perspectives for the assessment of prosthetic knee implants, particularly the patellofemoral tracking, including in the design phase.

Conflict of interest

None.

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